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DYNAMIC RESPONSE OF SATURATED FIBRE-REINFORCED SAND

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ABSTRACT

Liquefaction has been causing severe damage during and after earthquakes. A number of countermeasures to liquefaction have been proposed and, to varying degrees, implemented. Fibre-reinforcement, a potential one, has shown its effectiveness in a large number of element laboratory tests. As element testing represents only a small element of soil rather than the full boundary value problems, small scaled physical modelling needs to be performed for this to be accepted as a workable solution. Two bi-layer centrifuge models with level ground surface subjected to Kocaeli earthquake have already been performed. In the top layer, one test consisting of loose clean sand susceptible to liquefaction was conducted as the reference and the other with fibre-reinforced sand of the same relative density was for showing the improvement of dynamic response by adding fibres. These two tests can be regarded as simulation of free field as well as 'super element' tests with real boundary condition. Results suggest that adding fibres increase the liquefaction resistance by increasing excess pore pressure generation time and softening required shear stress cycles, but the reduction of ground surface settlement and maximum excess pore pressure are not significant. Further investigation with other initial stress conditions needs to be conducted

1. INTRODUCTION

Since 1964 Niigata earthquake, severe damage caused by liquefaction has provoked people's attention. In recent decades, numerous liquefaction mitigations have been taken into investigations and applications such as densification techniques, drainage techniques, physical and chemical modification techniques and inclusion techniques (Adalier, 1996).

Fibre-reinforcement has aroused the interest of geotechnical researchers and engineers since early 1980s and this technique has shown its feasibility in improving pavement layers, retaining walls, railway embankments, protecting slopes, earthquake engineering and soil-foundation engineering (Hejazi et al., 2012).

A large number of monotonic loading tests, mainly direct shear tests and triaxial tests, has verified the benefit of fibres in improving shear strength, reducing post strength of the composite, and the existence of a critical confining stress below which fibres tend to slip or pull out from the sand matrix (Gray and Ohashi, 1983, Maher and Gray, 1990, Al-Refeai, 1991, Michalowski and Čermák, 2003). Static liquefaction is prevented by adding fibres and collapsed structure of specimen after shear tests, which showed by unreinforced specimens, were not observed (Ibraim et al., 2010), indicating that the presence of fibres limit the occurrence of lateral spreading of liquefied soils.

Limited research on dynamic response fibre-reinforced is mentioned in literatures. Outcomes of cyclic triaxial tests conducted by Noorany and Uzdavines (1989) shows the higher liquefaction resistance than other reinforce configurations. The contribution of fibres in increasing liquefaction resistance was also verified by Krishnaswamy and Thomas Isaac (1994) and it is also feasible to fly ash (Boominathan and Hari, 2002). 1-g shaking table tests conducted by (Maheshwari et al., 2012) demonstrate that adding fibres was beneficial in reducing excess pore pressure generation and ground surface settlement.

As the limitation of element test to simulate real boundary condition and low confining stress imposed by self-weight in 1-g shaking table tests, centrifuge tests, which is able to simulate real boundary conditions more closely, needs to be conducted to investigate the dynamic response of saturated fibre reinforced sand in real conditions.

In this paper, effects of fibres on generation of excess pore pressure, composite softening and dynamic shear modulus of the composite are presented. Possible reasons for obtaining different results of this study compared with previous studies are discussed

2. CENTRIFUGE MODELLING

2.1 Equipment

Tests were performed by the Actidyn C67-2 geotechnical centrifuge with newly installed Actidyn QS67-2 inflight 1-D hydraulic earthquake simulator which is able to cover the frequency range over 40Hz to 400Hz and displacement range of ±2.5mm (Bertalot et al., 2012, Brennan and Knappett, 2014). Soil models were constructed in an equivalent shear beam (ESB) container with inside dimensions of 674×280×312mm^3. This container is designed to match the vibration performance of dry sand to minimize the boundary effect and this adverse effect is negligible to the central area of the saturated models. Accelerometers (ACCs), miniature pore pressure transduces (PPTs) and linear variable differential transformers (LVDTs) were set for collecting data.

2.2 Materials

The models were built by HST95 Congleton sand. This sand has D_{10}=0.1mm, D_{30}=0.12 mm and D_{60}=0.14mm. The maximum void ratio is e_{max}=0.795 and the minimum void ratio is e_{min}=0.463. Fibres used for reinforcement was crimped polypropylene fibres with a commercial name Loksand^{TM}. The nominal length of this fibre is 35mm, nominal diameter of the round section is 0.1mm and tensile strength is 200MPa (provided by the manufacturer). The substitute of water for saturating the model was methylcellulose solution with 50 times viscosity of water to eliminate the discrepancy caused dynamic time and dispassion time (Taylor, 1995).

2.3 Model Description and Construction

Model section view and instrument layout are shown in Fig.1. The general model consists of two layers: upper loose layer (or fibre-reinforced loose layer) with a thickness of 200mm (10m in prototype) and 80 mm dense layer (4 m in prototype). Relative density (D_r) of the loose layer was 40% and that of dense layer was 80%. ACCs and PPTs were placed in a vertical array at prescribed key depths and LVDTs were fixed on a frame over the top of the container to measure ground surface settlement.

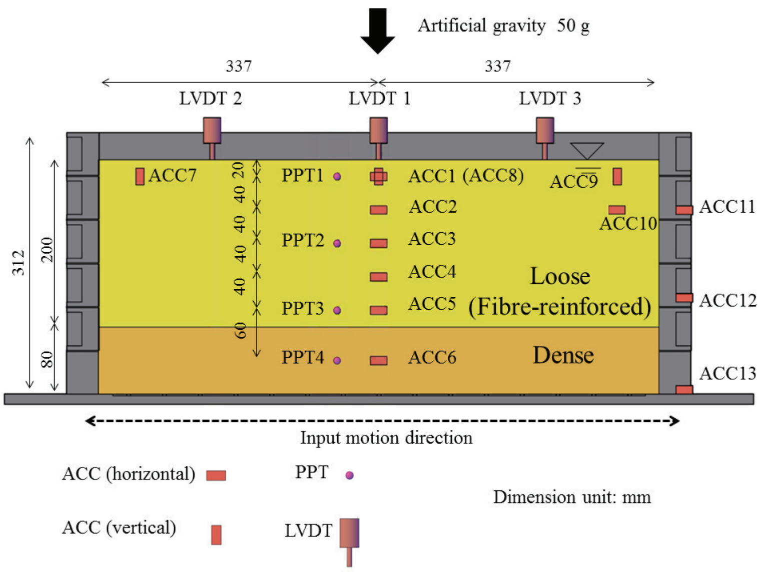

Figure 1 Section view of model and instrument layout

2.4 Test Programme

The two tests were conducted at 50g. Scaled input motion originated from Izmit station during Kocaeli earthquake, Turkey, 1999. This motion was selected as a representative of M_w=7.5 earthquake which in line with the simplified in-situ testing procedure (e.g. standard penetration test (SPT)). It is capable of liquefying soils but not so devastating that, to a large extend, success opportunity of liquefaction mitigation methods is limited. All units are in prototype in following sections unless specified.

3. RESULTS AND FINDNGS

3.1 Accelerations

Acceleration time histories of both tests are shown in Fig.2. The overall amplification/attenuation trend is similar with the variation of depth in both tests. Accelerations were amplified at the bottom of the model and then generally attenuated upward. Acceleration propagation, in loose clean sand deposit, began to attenuate drastically from 9m at which the depth approached to the bottom the loose deposit, which implied occurrence of liquefaction of the whole deposit as expected. In fibre-reinforced deposit, amplification of acceleration still occurred at that depth (9m) and started to attenuate gently at 7m. Amplitudes of attenuated accelerations in fibre-reinforced deposit at depths above 7m were larger than those in clean sand. It indicates that fibre reinforced sand is more capable in transmitting shear stress. In other words, saturated fibre-reinforced sand is less likely to be softened under the same seismic condition. More acceleration cycles were observed before the amplitude reduced to zero at 1m in fibre-reinforced sand, implying that fibres improve the resistance to softening caused by liquefaction.

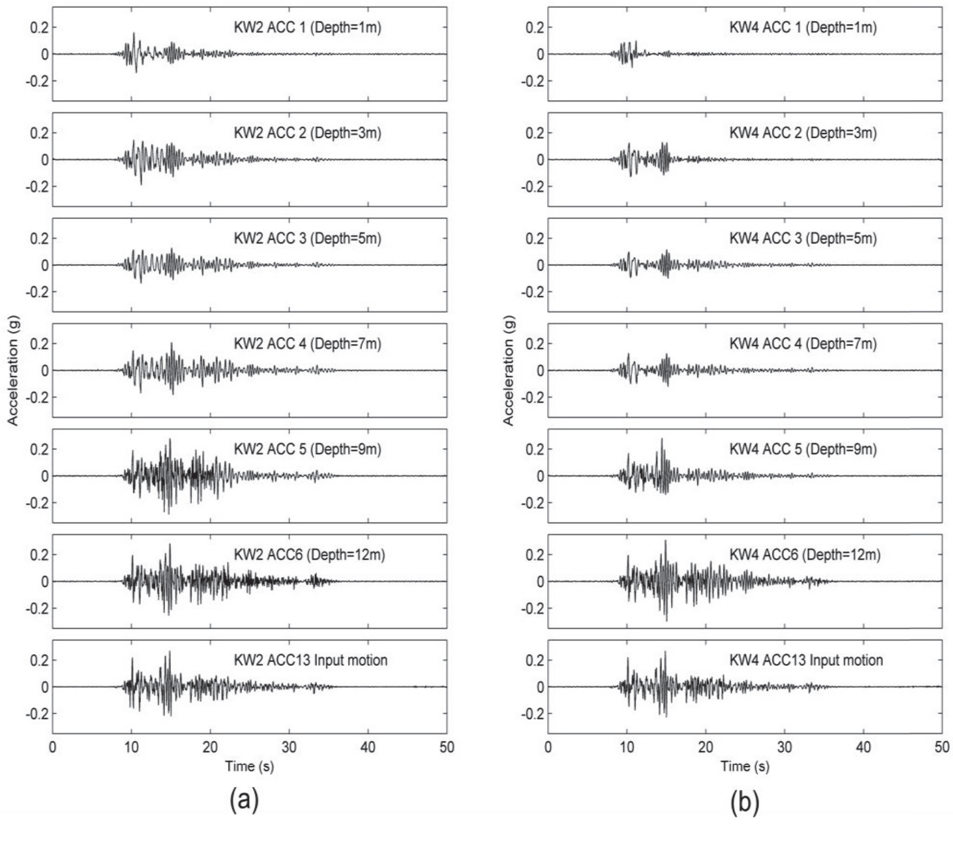

Figure 2 Acceleration time histories: (a) KW2 Fibre-reinforced sand; KW4 Clean sand

3.2 Stress Strain Relationships

The constitutive behaviour of the composite needs to be investigated for further inspection of effects of discrete fibre inclusions on the dynamic behaviour of saturated sand matrix. As acceleration attenuation caused by the generation of excess pore pressure, reliable representative shear modulus become more difficult parameters to be obtained (Brennan et al., 2005). Only a representative cycle (during an overall period of 9.2s-9.75s) before significant excess pore pressure generation is presented at each depth. The calculation method of shear stress, shear strain, and shear modulus are mentioned in detail in the work conducted by Brennan et al. (2005).All the representative parameters at various depths are depicted in Fig.4.

Calculated absolute shear modulus rises with increasing depth (i.e. confining stress) in both tests but the contribution of fibres to shear modulus reduces, which is consistent with the conclusions conducted by Maher and Woods (1990).

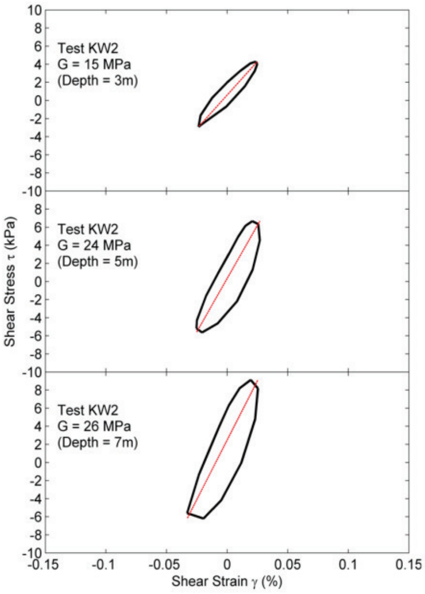

Figure 3 Shear stress shear strain relationships at various depths:
(a) KW2 Fibre-reinforced sand; KW4 Clean sand

3.3 Excess Pore Pressures

Fig.5 shows excess pore pressure generation and dissipation of these two tests. Almost the same maximum excess pore pressure and similar dissipation process were observed in both tests at each depth, but the generation process was influenced by the presence of fibres. In the fibre-reinforced sand, more time were needed in test KW2 to reach the maximum value at depth 5 m and 9m. Apparent spikes shows at the early stage of the excess pore pressure generation process at 1 m, which indicates the occurrence of transient dilation during that period.

From these results, it can be interpreted that fibre-reinforced sand needs more stress cycles to be liquefied so that liquefaction resistance are improved. This result has also been verified by previous element tests (Noorany

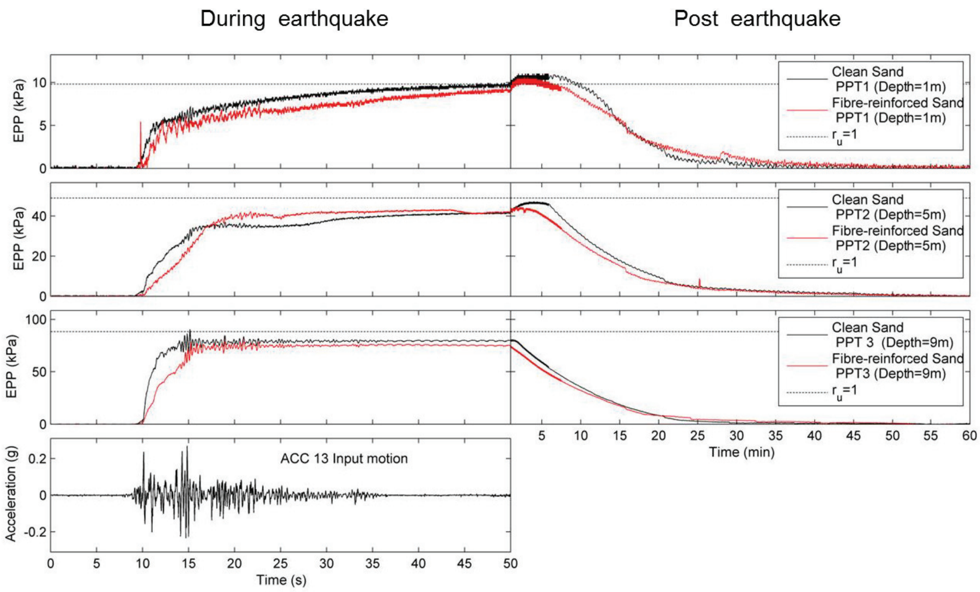

Figure 4 Excess pore pressure generation and dissipation

and Uzdavines, 1989, Krishnaswamy and Thomas Isaac, 1994). Maximum r_u (ratio of excess pore pressure to initial effective overburden stress) in both tests approached to unity (liquefaction criteria) may due to that the input motion are strong enough (enough stress cycles) to cause liquefaction in both deposits.

3.4 Settlements

Ground settlements are illustrated in Fig.6. As parasitic vertical oscillation caused much noise in measurement, the obtained data was filtered with 8th order Butterworth low pass filter with a cut off frequency of 5Hz. Ground surface settled in a similar way in both tests during and after motion input periods. As there was no external static shear stress (e.g. shallow foundation) imposed to the ground, all the settlements were caused by the volumetric strain. Fibre inclusions did not show significant influence on liquefaction induced settlement in the condition of this study.

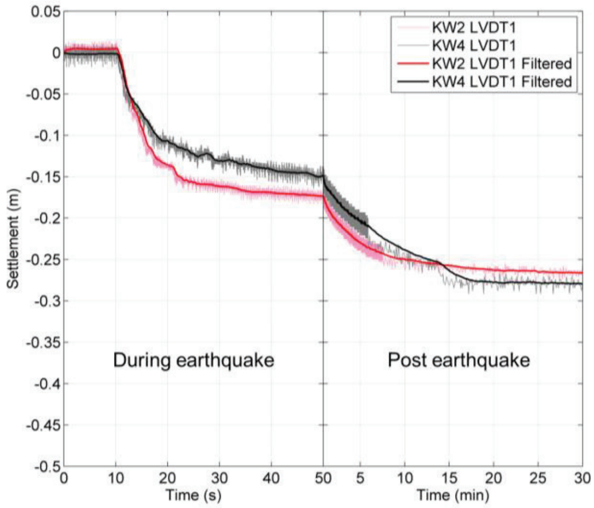

Figure 5 Ground surface settlement time histories

4. DISCUSSIONS

Fibres show their contributions to increase the liquefaction resistance by increasing required stress cycles to reach the maximum excess pore pressure value. Improvement provided by fibres to shear modulus reduced with increasing depth, which may be caused by the dominant governance of particle inter-friction to shear modulus under high confining stress (Maher and Woods, 1990). Although the properties of composite are improved by fibres, their contribution in this study is still not as significant as those mentioned by Maheshwari et al. (2012) who conducted similar 1g shaking table tests on saturated fire-reinforced sand. This may due to less overburden pressure in 1-g shaking table tests, under which dilative behaviour of fibre-reinforced sand is more significant. Also larger shear strain induced by more sever shear stress in those 1-g shaking table tests may also induce larger shear strain to promote the dilation of fire reinforced sand while shear stress was greatly deamplified during upward propagation in the centrifuge tests of this study.

The outcome, from this study, that more time is needed to build up excess pore pressure in fibre-reinforced sand keeps the consistence with that from 1-g shaking table tests. This may due to that presence of fibres make sand particles more difficult to move when subjected to seismic motion and more load needs to be imposed to reach the final contractive volume change.

Ground surface settlement was reduced with the contribution of fibre in 1-g shaking table tests, but no significant influence was observed in this study. This may also due to small shear strain level in which influence of fibres to contractive volumetric change is not obvious (Ibraim et al., 2010) in centrifuge tests.

5. CONCLUSIONS

Fibre-reinforced sand shows some improvement in liquefaction resistance. More shear stress cycles are required before reaching the maximum excess pore pressure and being fully softened. Contributions of fibre are also found in enhancing dynamic shear modulus, but it drops with increase of confining stress. The influence of reducing maximum excess pore pressure and ground surface settlement is not as significant as pervious in 1-g shaking table tests, which may imply the over estimation of contribution of fibres just from 1-g shaking table tests. Further investigation on liquefaction induced hazard with initial shear stresses (e.g. shallow foundation settlements, lateral spreading) should be conducted in the future work.

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